

Development and Evaluation of Innovative Arsenic Adsorption Technologies for Drinking Water by the Arsenic Water Technology Partnership (SAND2006-0113C)

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Presentation at the 2006 NGWA Naturally Occurring Contaminants Conference
Albuquerque, NM, February 6-7, 2007

The decrease of the maximum contaminant level (MCL) for arsenic in drinking water from 50 parts per billion (ppb) to 10 ppb in January 2006 will lead to significant increases in the cost of water for many rural systems throughout the United States. The Arsenic Water Technology Partnership (AWTP), a collaborative effort of Sandia National Laboratories, the Awwa Research Foundation (AwwaRF) and WERC: A Consortium for Environmental Education and Technology Development was formed to address this problem by developing and testing novel treatment technologies that could potentially reduce these treatment costs. Each of the Partners develops or evaluates new technologies in their respective programs: AwwaRF manages a bench-scale research program through a series of competitive grants; Sandia Labs evaluates cutting-edge commercial products in an annual Vendors Forum; and WERC hosts an annual contest in which university students compete to provide the best solution to a design challenge involving arsenic treatment. The technologies that show the most promise are then tested at the field scale by Sandia National Laboratories at several sites in New Mexico and in other states.

During the first two years of the Partnership, over 100 innovative technologies were reviewed. Improvements in fixed bed adsorption treatment processes involve 1) metal oxide or resin-based fixed bed adsorbent media with high selectivity, capacity and mechanical strength and 2) coated inexpensive natural or synthetic materials with a reactive surface with high selectivity for arsenic. Examples that illustrate the underlying scientific and engineering principles for improvements in sorption treatment processes are drawn from the Vendors Forums, the WERC Design contest and on-going research projects of AwwaRF.

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Introduction: the Arsenic Water Technology Partnership

The Arsenic Water Technology Partnership (AWTP) is a multi-year program funded by a congressional appropriation to evaluate and develop new technologies that could significantly reduce the costs associated with compliance with the new maximum contaminant level (MCL) for arsenic in drinking water (10 ppb). The Partnership (<http://www.arsenicpartners.org/>) is a collaborative effort of Sandia National Laboratories, the Awwa Research Foundation (AwwaRF) and WERC: A Consortium for Environmental Education and Technology Development. As described below, each of the partners develops or evaluates new arsenic treatment technologies in their respective programs. The technologies that show the most promise are then tested at the field scale by Sandia National Laboratories at several sites in New Mexico and in other states.

AwwaRF manages a bench-scale research program through a series of competitive grants. The Research Foundation manages their projects in a fashion that is comparable to established AwwaRF processes. These processes include convening a panel of outside experts (Technical Review Committee) to set research objectives, issuing Requests for Proposals and the formation of peer review groups (Project Advisory Committees or PACs) which are composed of utility, academic, consultant and regulatory volunteers. PACs competitively review proposals, select the researcher, and monitor the project through completion. Research projects may have several phases, ending in selection of a promising technology to be tested at the pilot scale by Sandia Labs. Attachment A describes the projects that seek to develop new adsorptive media. More details about the AwwaRF program can be found at <http://www.awwarf.org>.

Sandia National Laboratories has evaluated cutting-edge commercial products in annual Vendors Forum that were held as part of the New Mexico Environmental Health Conference in Albuquerque, NM. At the open session of Forums, commercial developers of innovative treatment technologies described project histories that demonstrate the effectiveness of their products. At a subsequent closed session, these same technologies were evaluated by independent technical experts for possible use in pilot demonstrations to be conducted by Sandia Labs at community sites. The technologies were evaluated in 6 categories: 1) performance, 2) level of maturity and viability of the company, 3) costs, 4) implementability (i.e. regulatory acceptance), 5) effects on the user community, and 6) degree of innovation. Attachment B describes the participants that presented information about adsorptive media at the three Vendors Forums (2003-2005) and identifies the top ranked technologies. More details about the Vendors Forums can be found at <http://www.sandia.gov/water/arsenic.htm>.

WERC hosts an annual contest in which university students compete to provide the best solution to a design challenge involving arsenic treatment. The contest, now in its sixteenth year, provides university and college teams with the opportunity to research, design, develop and deploy practical solutions to real world environmental and human health challenges facing this nation. Held at New Mexico State University in Las Cruces, New Mexico, the contest draws hundreds of college students from throughout the United States and around the world. The student teams design solutions for real-world problems

while developing fully operational bench-scale solutions that are presented to panels of judges comprised of environmental professionals. Over the last three years of the contest, 28 teams have participated in the arsenic design challenge problem. Attachment C describes the contest winners and other innovative projects that utilize adsorptive media. More information can be found at <http://www.werc.net/contest/>.

In the Partnership programs, several innovations that could lead to lower treatment costs have been proposed for adsorptive media systems. The scientific and engineering principles that underlie adsorptive processes important for these innovations are summarized in the next section. Examples that illustrate these principles are then drawn from the Vendors Forums, the WERC Design contest and on-going research projects of AwwaRF.

Controls on adsorption of arsenic in fixed bed media:

To a first approximation, the effectiveness of fixed bed adsorptive media for arsenic removal depends on 6 factors:

- 1) pH of the solution
- 2) redox speciation of As (i.e. As(III)/As(V) ratio),
- 3) concentration of aqueous species that will interfere with adsorption of arsenic by competing for adsorption sites or modifying adsorptive media surface charge,
- 4) concentration of aqueous and colloidal species that interfere with the uptake of arsenic by physically blocking access of arsenic to the interior of the particles or grains of adsorptive media,
- 5) surface area and pore size distribution of the adsorptive media, and
- 6) hydraulic properties of the media during treatment

The first 4 of the above factors are linked by chemical equilibria between the various aqueous species in the water entering treatment media; the fourth and the last two factors are affected primarily by physical mass transfer processes and media properties as discussed below.

Chemical controls

The pH of the solution influences sorption by its effect on the charge of the sorbing aqueous arsenic species and on the surface charge of the media. Figure 1 shows the pH dependence of the hydrolysis of arsenate (As(V) and arsenite (As(III)), the most common oxidized and reduced arsenic species, respectively, in natural waters. At pH's typical of natural waters, arsenate is negatively charged; above a pH of about 9, arsenite also exists predominantly as an anionic species.

Table 1 lists the pH of the zero point of charge (ZPC) of several metal oxide sorbents commonly used as fixed bed adsorbents for arsenic. Above the pH of the ZPC, the surface has a net negative charge and there will be an electrostatic repulsion between an anionic species and the surface. If sorption is to occur by a specific chemical bond, this repulsion must be overcome. The net effect of pH on arsenic sorption by iron oxyhydroxide is illustrated in Figure 2. Arsenate is more strongly sorbed and is more

affected by pH over the pH rang 4 – 9 compared to arsenite, above pH of about 9, arsenite sorption is predicted to be relatively higher than that of arsenate.

Table 1. pH of Zero Point of Charge (pH_{ZPC}) for metal oxyhydroxides used in arsenic treatment (from Yoon et al. 1979)

oxide	Al(OH) ₃	TiO ₂	α-FeOOH	α-Fe ₂ O ₃	CuO	La ₂ O ₃	ZrO ₂
pH _{ZPC}	5-9.1	6.7	6.7	9.0	9.4	10.4	10-11

If the arsenic species overcome the electrostatic repulsion and approach the surface, spectroscopic studies indicate that arsenite and arsenic form strong inner sphere surface complexes with the sorbents. (Fendorf et al., 1997) However, other anionic species that are present in groundwaters at 2 or 3 orders of magnitude higher than arsenic will compete for the sorption sites. Speciation and sorption diagrams similar to Figs 1 and 2 can be constructed for these other groundwater constituents (e.g. F⁻, PO₄³⁻, SO₄²⁻, VO₄³⁻, SiO₂); they indicate that sorption of these solutes is also dependent on solution composition. A sorbent will effectively remove arsenic only if it is highly selective for arsenic species under the chemical condition (pH, redox, concentration of competing species) of the water. In general, sorption selectivity for iron oxyhydroxides and alumina is: (Clifford, 2003) .

OH⁻ > H₂AsO₄⁻ > H₂PO₄⁻ > Si(OH)₃O⁻, VO₄³⁻, > F⁻ > HSeO₃⁻ >> TOC > SO₄²⁻ >> Cl⁻, NO₃⁻, HCO₃⁻ > H₃AsO₃

Physical controls

Figure 3 describes important physical processes involved in uptake of arsenic by adsorbent media. Note the concentration axes on the right side of the figure. The concentration of arsenic decreases from c_b in the bulk solution, to c_s at the fluid solid interface, to c_p in the pores, as q, the concentration in the solid, increases. In dynamic systems, such as fixed bed treatment systems, the effectiveness of arsenic adsorption is dependent on the relative rates of several processes. These include: 1) kinetics of chemical surface complexation; 2) the kinetics of mass transfer of arsenic to the interior of the grains, and 3) the hydraulic loading rate (flow rates). The effectiveness of treatment will be highest when the arsenic species form specific chemical bonds quickly to reactive surfaces and the flow rate is low enough to allow arsenic species to migrate to fresh sorption sites in the grain interiors. High surface area and a uniform pore distribution with a mean pore size large enough to allow diffusion of the aqueous species lead to high sorption capacity. This capacity however can be diminished in the presence of high concentrations of SiO₂ and organic matter, which will coat the surfaces of the grains and prevent arsenic species from reaching reactive sorption sites. (Meng et al. 2000; Grafe, et al. 2001, Davis et al. 2002)

In a flowing system, the balance between these rates is expressed by the shape of the mass transfer zone in which the concentration of the arsenic drops from its initially high value to a lower value corresponding to equilibrium sorption. In the current application to drinking water treatment, the adsorbent bed must be replaced or regenerated when the concentration of arsenic in the effluent exceeds the MCL (10 ppb).

Under favorable conditions where diffusion into the grain interior is rapid relative to hydraulic loading rate, the mass transfer zone will be relatively sharp and a large fraction of the potential sorption capacity of the media will be utilized before replacement is warranted. Under unfavorable conditions, the mass transfer zone will be broad, the arsenic concentrations in the effluent will rise rapidly above the MCL, and most of the adsorbent bed will not adsorb arsenic before it needs to be replaced.

Improvements for fixed bed adsorbent media

Based on the principles outlined in the section above, the key to improving performance of sorbent media is to use a material with a neutral or net positive charge surface charge in the water of interest and that forms strong covalent bonds with the prevalent aqueous arsenic species. In addition, a large concentration of accessible reactive sorption sites at the surface and interior of the medium will lead to high arsenic adsorption capacities. A uniform distribution of mesopores (20 – 500 Å) will facilitate mass transfer and lead to sharp mass transfer zones. The hydraulic and mass transfer properties of the media must also remain constant and favorable during media service. Clogging of media by precipitated solids, blocking of sorption sites by surface precipitates or comminution of the particles resulting in production of fines will all decrease the useful life of even the most sorbent media bed. Thus increased physical durability may improve the performance of the media in the treatment system.

Improved performance of arsenic adsorbent media has been demonstrated or claimed for several technologies evaluated by the AWTP. Innovations include: 1) higher capacity and selectivity using mixed oxides composed of iron and other transition metals, titanium and zirconium based oxides, or mixed resin-metal oxides composite media, 2) improved durability of virgin media and greater chemical stability of the spent media, and 3) use of inexpensive natural or recycled materials with a coating that has a high affinity for arsenic. These innovations are summarized below; more information about specific technologies is found in Attachments A-C.

Metal oxhydroxide adsorbents

New media, composed of Fe, Ti, Cu, Zr or mixed metal oxides in granules formed by chemical precipitation or nanoparticle agglomeration (e.g. AdEdge, Kemiron, Englehard, Graver, MEI, MARTI; see Attachment B), may have improved performance at relatively high pH (>8). This is due to their higher ZPC compare to activated alumina, the adsorbent media classified by the USEPA as a Best Available Technology (see Table 1). Many existing metal oxide media, are produced from solids through metal salt and strong acid addition with evaporative processes that produce uncontrolled pore-structure resulting in mediocre mass transfer kinetics. MEI uses ZrO₂ microparticles mounted to a membrane in a patented cartridge system to improve mass transfer kinetics. In a novel approach taken by Arizona State University and Graver, nanoparticles (5 to 50 nm in diameter) are agglomerated using polymeric binders into porous media particles (0.5 to 1 mm diameter). Nanoparticles have high surface areas since they are small in diameter, and the agglomerated porous media have high surface area. Other AwwaRF projects (see Attachment A) seek to dope Ti and Zr oxide nanocomposites with transition metal ions

Mn⁺² and Fe⁺³ to increase their specific surface area (SSA) and porosity. Finally, both Kemiron and AdEdge claim superior durability for their products compared to other media.

Coated synthetic materials

Adsorbent media produced by coating granular activated carbon (GAC), strong base anion exchangers (SBA) resin or polymeric ligand exchangers (PLEs) with nanoparticulate metal oxides take advantage of the favorable and uniform pore size distribution of their substrates. (e.g. Purolite, Resintech, Arizona State, Penn State, Auburn University). These media can have high selectivity, capacity and mechanical strength and can be regenerated fairly readily. Purolite and Resintech manufacture strong base anion exchange resins with iron oxyhydroxide coatings on the micron-scale level or suspended in the resin at the atomic level. GAC has a higher surface area than porous metal oxides. At Arizona State, iron oxides are impregnated into GAC pores, ideally providing only monolayer coverage of the internal surface area. Alternatively, GAC preloaded with citrate-iron or EDTA-iron is being studied for removing arsenic at Penn State. At Auburn University, PLEs demonstrated orders of magnitude greater selectivity for arsenate than the commercially available standard SBA resins. Among the three PLEs studied in detail, DOW 3N-Cu appears to be the most promising to achieve highly selective removal of arsenate in the presence of high concentrations of competing anions such as sulfate.

Coated natural materials and waste products

Adsorbent media produced by coating inexpensive natural media or waste products with metal oxides or other functional groups may provide low cost media albeit with relatively low sorption capacity. (e.g. ADA, Virotec, EaglePicher, Lawrence Berkeley Labs). The ADA media is a low-density natural alumina silicate coated with nanoscale iron oxyhydroxide (akaganeite). The EaglePicher media is a lanthanum-coated nanocrystalline diatomaceous earth that should be effective at higher pH due its relatively high pH_{ZPC} (see Table 1). Bauxsol, the media from Virotec, Inc is produced from waste products of bauxite production. It is a cocktail of metal oxyhydroxides that is purported to remove arsenic by a variety of processes. The media produced by Lawrence Berkeley lab is based on fly ash, another waste product, which is coated by ferric oxyhydroxide. Whether the use of inexpensive substrates will be cheaper than that associated with the higher cost-higher capacity media described in the previous sections will be ultimately determined by the free market. ADI International, Inc (www.adi.ca) and WRT, LLC (www.wrt.net), two companies that have not participated in the Partnership program, have taken this approach and are carrying out pilot tests throughout the country.

Other innovations to improve media performance

Other methods are being used to produce adsorbent media with high surface area and chemical selectivity based on fibrous or gel substrates coated by metal oxides (e.g. Argonide, Arizona State, NMSU, Lafayette University, Drexel University). Argonide Corp. manufactures a nano-alumina fiber (2 nm diam) which can be woven into filters. It

is electropositive and effective for arsenic removal at circumneutral pH (6.5) but less effective at alkaline pH. Researchers at Arizona State have developed arsenic removal media made of aerogels, which are open-foam-like structures with high surface areas, low densities, and high porosity. Composite materials (aerogel plus GAC) are formed by mixing hydrophobic sol-gel precursors with chemical agents, including those with iron and manganese functional groups, gelation catalysts, and GAC. The resulting aerogel-GAC composite has aerogel within the GAC pores and very high surface area containing accessible iron-manganese binding sites and has been demonstrated in preliminary experiments to remove arsenic. At Drexel University, researchers are evaluating the potential of iron-oxide-coated fibers as an arsenic treatment process for drinking water by screening fibrous materials using isotherm data to identify the most promising material. Studies will also assess the ability of the iron oxide to be removed by physical processes, which would permit the fibers to be reused and evaluate several alternative coating procedures.

Both NMSU and Lafayette College received funding from WERC to further develop their technologies presented at the WERC design contest. NMSU developed a sol-gel derived mesoporous activated alumina adsorbent. The sol-gel has a large surface area, large pore volume and very uniform pore size. Column experiments show high dynamic capacity and high bed utilization efficiency. Lafayette College has been working to refine their iron-enhanced activated alumina. Several groups have proposed use of other materials in sorbent media such as bone char, humic material and collagen (Brimac, Arctech, Widener University; see Attachments B and C.)

Conclusions

Ultimately, adsorbent media performance must be evaluated with respect to overall treatment cost. The capital equipment such as reaction vessels, pumps and plumbing will be the major initial cost and will likely be financed by water utilities. The media cost, however, could dominate the operations cost and may be significant over the lifetime of the treatment plant. This cost can be minimized either by using very cheap materials or by using more expensive materials with higher arsenic removal capacity. Both of these approaches are represented by the technologies evaluated by the AWTP.

During 2005, Phase I pilot tests were conducted with 11 adsorptive media evaluated at the Vendors Forums (see Attachment B) at 3 different sites in New Mexico (Aragon et al. 2006). Results of these tests will provide side-by-side comparisons of the effectiveness of different media in different ground water compositions. When combined with cost models developed by the AWTP and others, the results should provide guidance to communities in selection of the best commercial technologies for their needs. In 2006 and 2007, Phase II pilot tests will be conducted with new media developed under the AwwaRF and WERC programs described above and by other research efforts. The results of these tests will identify the innovations that truly have the potential to reduce the cost of compliance with the new MCL for arsenic in drinking water.

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Figures

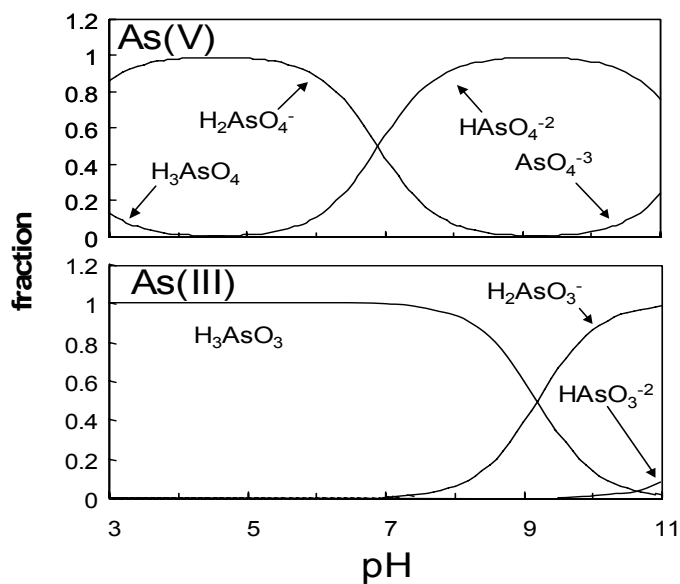


Figure 1. Speciation of aqueous arsenic (III) and (V) as function of pH (from Brady et al. 2004).

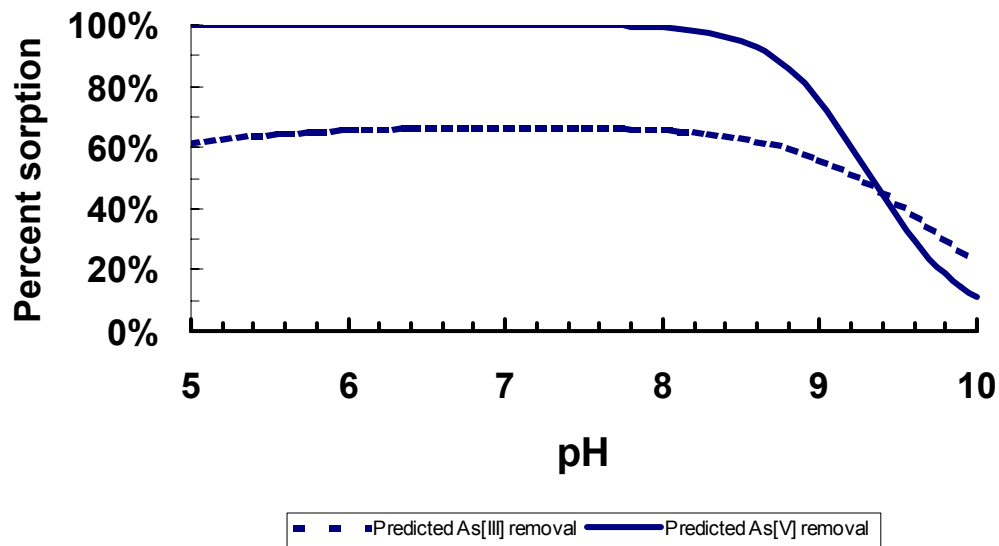


Figure 2. Calculated relative removal of 50 ppb As(III) or 100 ppb As(V) by ferrihydrite as function of pH in 0.01 M NaNO_3 with 3 ppm Fe(III). Constants from Dzombak and Morel, 1990).

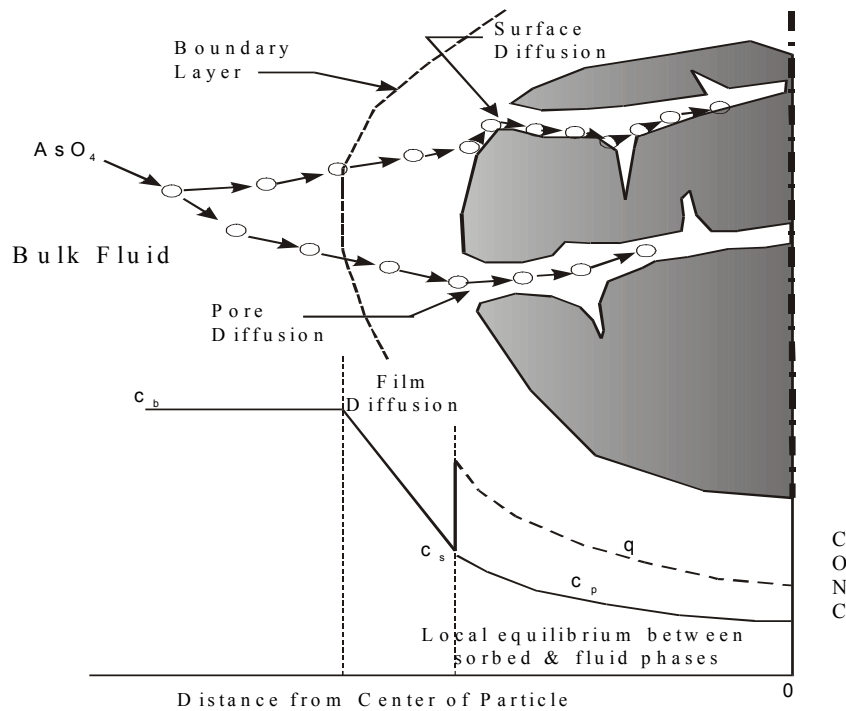


Figure 3. Processes controlling transport of arsenic from bulk solution to interior of granular adsorbent media (Aragon, 2004).

Attachment A. List of Selected Projects for Adsorptive Media Funded by AwwaRF
(A full list of AwwaRF-funded AWTP projects can be found on the AwwaRF website at <http://www.awwarf.org>)

#3076 Developing a New Class of Ion Exchangers for Selective Removal of Arsenic and Exploring an Engineering Approach for Treatment and Reuse of Spent Regenerant (Auburn University)

The research objectives are to develop and characterize a new class of innovative IX materials, referred to as polymeric ligand exchangers. Unlike conventional IX resins, PLEs can selectively remove As(V), and their capacity for arsenic removal is at least three times greater than that of commercial sorbents. Moreover, PLEs can be regenerated efficiently by brine at an alkaline pH, and the same brine can be reused more than five times without treatment. The arsenate capacity of a new resin (DOW 3N-Cu) is 17 times greater than of standard Strong Base Anion exchange resins based on the Langmuir capacity coefficient. Fixed-bed column experiments confirmed that the high arsenic capacity and selectivity of the PLEs. The breakthrough curves indicate the following affinity sequences: $\text{HAsO}_4^{2-} \gg \text{HCO}_3^- > \text{SO}_4^{2-} > \text{Cl}^-$ for the PLEs. In addition to the high arsenate selectivity, the PLEs also exhibit reasonably fast sorption kinetics. The diffusivity value (D) for DOW 3N-Cu was determined to be $\sim 1.0 \times 10^{-7} \text{ cm}^2/\text{s}$, which is comparable to that for standard macroporous ion exchange resins.

#3077 Agglomerated Nanoparticle Media (Arizona State University)

Nanosized particles (5 to 50 nm in diameter) are agglomerated using polymeric binders into porous media particles (0.5 to 1 mm diameter). Nanoparticles have high surface areas since they are small in diameter, and the agglomerated porous media have high surface area. The agglomeration approach is applied in (MetSorbG), an agglomerate of 6.6 nm TiO_2 nanoparticles. The approach differs considerably from existing metal oxide media, which are produced from solids through metal salt and strong acid addition with evaporative processes that produce uncontrolled pore-structure development. The goal of this project is to demonstrate that agglomerated nanoparticle media will remove arsenic effectively, allow more rapid mass transport of arsenic into the media, and have reduced headloss and, possibly, increased selectivity compared with aluminum- or iron-based media.

#3079 Aerogel and Iron-Oxide Impregnated Granular Activated Carbon Media (Arizona State University)

This project is investigating the use of iron-oxide-impregnated GAC and iron-manganese-aerogel GAC-composite materials. GAC has higher surface area than porous metal oxides; iron oxides can be impregnated into GAC pores, ideally providing only monolayer coverage of the internal surface area. Aerogels are open-foam-like structures with high surface areas, low densities, and high porosity. Composite materials (aerogel and GAC) are formed by mixing hydrophobic sol-gel precursors with chemical agents, including those with iron and manganese functional groups, gelation catalysts, and GAC. The resulting aerogel-GAC composite has aerogel within the GAC pores and very high

surface area containing accessible iron-manganese binding sites and has been demonstrated in preliminary experiments to remove arsenic and organic contaminants simultaneously.

#3080 Innovative Arsenic Removal Onto Activated Carbon That Is Preloaded With Surfactant-Iron Complexes (Penn State University)

#3163 Arsenic Removal With Activated Carbon Tailored With Organic Carboxyl - Metal Complexes That Perform at Neutral pH (Penn State University)

The investigators preload surfactant-iron complexes onto selected granular activated carbons (GACs) to enhance arsenic removal. In small municipalities, a practical way to implement this protocol in full-scale systems will be to employ several vessels in series: the first vessel will be filled with steel or iron filings that are intended to corrode; and this corrosion could be prompted by slight acidic pH adjustment (to about pH 6.0). This iron bed will precede one or two GAC beds that are tailored with iron-organic acid. The slight acid will cause the iron to corrode; and the corroded iron will efficiently capture arsenic while it also associates with a ligand (either hydroxide or organic acids). The iron-arsenic complexes can then be either sorbed into the tailored GAC media, or they can precipitate and deposit as flakes above the GAC media. Thus, not only will the GAC serve as a filter, it will also serve as a polishing sorbent of the dissolved iron-arsenic complexes. Under circumstances similar to those simulated above, the iron bed could be about a fourth of the size of the GAC beds. With this protocol, the arsenic removal process could go on for probably quite a bit longer than the 150,000 BV, the materials costs for removing arsenic would be \$5-20/acre foot (0.15-0.6 cents per 1000 gallons).

In the second project (#3163), GAC preloaded with citrate-iron or EDTA-iron is being studied for removing arsenic from drinking water down to 10 ppb or less. Ways to tailor the bed to operate at neutral (unaltered) pH while processing primarily As(V) water will be investigated.

#3161 Removal of Arsenic by Sorption to Iron-Coated Fibers (Drexel University)

Researchers are evaluating the potential of iron-oxide-coated fibers as an arsenic treatment process for drinking water by screening fibrous materials using isotherm data to identify the most promising material. Studies will also assess the ability of the iron oxide to be removed by physical processes, which would permit the fibers to be reused and evaluate several alternative coating procedures. The most promising material(s) and coating process will be tested in column tests to identify appropriate packing procedures and empty-bed contact times for use in a subsequent pilot study.

#3166 Low-Cost Arsenic Removal With Treated Coal Ash (Lawrence Berkeley Labs)

This research will further study the ability of bottom ash coated with ferric hydroxide to react with, remove, and immobilize arsenic in water supplies. It will investigate the influences of temperature and pH on removal chemistry and determine the regenerative potential of the media. The reaction rates for key steps in the process will be modeled.

Attachment B. Participating Vendors in Arsenic Treatment Technology Vendors Forums: Albuquerque, New Mexico 2003 – 2005

Vendor (Forum year) Type of adsorbent	Vendor's Description of Technology
ADA Technologies (2005) amended (coated) silicates	Amended Silicate™ sorbents are based on a process wherein active adsorption sites are distributed onto an inert, inexpensive silicate substrate. This amendment process can be tailored for the contaminant(s) of interest. The arsenic variant utilizes a ferric hydroxide amendment and has properties similar to other iron-based materials. However, the use of the inexpensive silicate substrate allows for efficient distribution of the iron at a low cost.
AdEdge Technologies (2003) Granular ferric oxide	Granular ferric oxide, applied in point-of-use, point-of entry and pre-engineered skidded community systems
APW Inc. (2004) GFO & TiO ₂ Media	Two products: Adsorb (Ferric Hydroxide) and Hedulit (Titanium Oxhydrate). These products, as of now, are being manufactured in Germany where they have been tested and used for years with ground and industrial waters. Our testing facility is in the University of Nevada, Reno. Our preliminary results have been very encouraging.
Arcotech, Inc. (2003) Humic material	Humasorb (2), a U.S. patented technology based on natural organic humic acid removes arsenic and other multiple toxic metals and organics in a low cost system for small scale and home use.
Argonide Corporation (2003,2005) Nano iron/alumina (Alfox GR-3)	Alfox is a granular material consisting of a proprietary nano alumina/nano iron hydroxide mixture. Laboratory testing shows it has about 2 to 2.5 times the EBV v. Bayoxide E-33. It is a higher bulk density and improved attrition resistance v. E-33.
Brimac Carbon Service Products (2005) Adsorption media (Brimac 216)	Brimac's adsorption media is a granular bone char adsorbent with dual components: carbon and hydroxyapatite [Ca ₁₀ (PO ₄) ₆ (OH) ₂]. The carbon surface adsorbs hydrophobic, lipophilic and weakly anionic molecules while the hydroxyapatite adsorbs strongly charged molecules together with many inorganic ions (metals).
Dow Chemical (2004) TiO ₂ Media	Dow has developed a patent pending granular media that is being designed for single use operations based from technology developed at the Stevens Institute of Technology. Our internal testing has shown that this titanium based product, formulated in our development labs, shows an improved capacity for arsenic over commercially available iron-based media.
EaglePicher Filtration (2004,2005) Adsorbent media (NXT-2)	The NXT-2 and NXT-CF are lanthanum hydroxide based medias for adsorption and coagulation/filtration arsenic removal, respectively. The lanthanum hydroxide provides pH stability up to pH10 and removes both As(III) and As(V) without the need for chemical pretreatment. Both medias also remove other contaminants such as phosphate, fluoride, selenium and others.

Vendor (Forum year) Type of adsorbent	Vendor's Description of Technology
Engelhard Corporation (2004) Granular Ferric Oxide	With ARM 200, Engelhard introduces a safe, efficient and cost-effective water purification treatment for the removal of arsenic from water. Key advantages of ARM 200 include: Effective removal of low levels of arsenic from drinking water. Certified safe for drinking water use under NSF 61. Removal of both forms of AsIII & AsV with no preoxidation or pretreatment required. Demonstrated arsenic removal capacity of greater than 99% even in the presence of competing ions. Engelhard ARM 200 is a specially tailored adsorbent designed for use in household filters, industrial, and water utility filtration systems.
Filtronics (2003) Composite filtration media - Macrolite	Process is oxidation, filtration with or without addition of less than 2 mg/L iron and without pH adjustment.
Graver Technologies HydroGlobe Division (2003,2005) Titanium oxide (MetSorb)	HydroGlobe MetSorb G is a nonregenerable titanium based media, available in a range of mesh sizes from powder to 16/60 mesh. Compared to competitive media, MetSorb G is less sensitive to common interferences such as silicates, phosphates, pH, and sulfates. It exhibits rapid kinetics, and hence low operating cost per thousand gallons of water treated. Disposal of the material is simple as a nonhazardous waste by TCLP and California WET tests.
HydroFlo, Inc. (2004) Cu-Oxide Media	Metal and Arsenic Removal technology (MARTI) a subsidiary of HydroFlo, Inc. distributes ARTI-64, an adsorbent media that removes both arsenate and arsenite to levels below the EPA and WHO limits. It requires with no pH adjustment, has rapid kinetics and produces no harmful byproducts. Performance is not affected by sulfates and the media can be regenerated.
Kinetico Inc. (2003) Various types	Kinetico provides several technologies including Coagulation Macrolite ceramic media filtration, iron bases and modified activated alumina adsorptive media, Ion exchange and POU cartridges and RO's. This wide variety of products allows us to evaluate a water supply and determine the best fit.
Magnesium Elektron, Inc. (2003) Powdered zirconium oxide	MEI has developed a series of novel adsorbent media for the purification of contaminated water. These zirconium-based media exhibit a wide range of improved performance in removing arsenic, chromium (III & VI), copper, and other metal and non-metal ions from drinking water, industrial process streams, and groundwater applications.
Purolite (2004,2005) Ion exchange and adsorptive medias (ArsenX-NP; A-530E; A-520E; A-300E; C100E)	Purolite's iron-impregnated anion resin, ArsenX-NP, will remove arsenic and uranium. Modifications incorporating A-530E, our perchlorate selective resin, and/or our C-100E cation resin will selectively remove perchlorate and radium as well. Brine regenerable SBA resins (A-520E and A-300E) will remove arsenic, nitrate, and uranium simultaneously.

Vendor (Forum year) Type of adsorbent	Vendor's Description of Technology
ResinTech, Inc. (2004,2005) Hybrid resin/adsorbent (ASM-10-HP)	Iron-based adsorbent monatomically dispersed in the gel phase of a strong base anion resin. Arsenic removal first occurs by ion exchange, and then arsenic is adsorbed into the iron. The hybrid resin has very rapid kinetics and is significantly more robust than competitive granular medias.
US Filter (2003) Granular ferric hydroxide	GFH is an adsorption process using ferric-based media to sorb arsenic and other heavy metals from raw water supplies. Once the media has exhausted its adsorption capacity, it is removed from the vessel and replaced with new media. The simplicity of this process is very attractive for small installations and wellhead applications especially where no treatment currently exists.
Virotec International Limited (2004) Adsorption (Bauxsol, Arsenic ProActiv)	Bauxsol™ has a high acid neutralizing capacity and an excellent ability to trap trace metals and metalloids. Trapped ions are tightly bound by mechanisms that include: precipitation of low solubility minerals, isomorphous substitution, solid-state diffusion, and adsorption. Bauxsol™ has an excellent ability to remove As(V) from water and field trials show the addition of Bauxsol™ to sulfidic rock reduced the As concentration in leachate from 35 to less than 0.005 mg/L. Arsenic concentrations have remained below 0.005 mg/L for five years since the treatment and concentrations of trace metals have remained well below regulatory limits.

Five Highest Ranked Adsorbent Media Vendors for each Forum (in order of raw composite scores)

Year	Company
2003	Hydroglobe(Graver), MEI, Kinetico, AdEdge, Filtronics
2004	Purolite, Engelhard, Filtronics, DOW, ResinTech
2005	Purolite, ResinTech, EaglePicher, ADA, Virotec

* Companies in bold font are currently being tested in Sandia Pilot Demonstration Program. In addition to these technologies, granular oxide media from Kemiron and Sandia Labs are being tested at the pilot sites.

More information about these technologies including evaluations, numerical scores and contact information can be found at the Vendor Forum websites accessible from <http://www.sandia.gov/water/arsenic.htm>.

Attachment C. Selected* WERC Design Contest Contestants: Adsorptive Media

School/ Technology	Description by Students
2003 Contest	
Michigan Tech/ Granular ferric oxide	Series of cartridges containing the AD-33L media from AdEdge
Montana Tech/ Fe-GS filter	Combined Fe-GS process that follows a three-stage removal scheme: includes zero valent iron and glauconitic sand (GS)
University of New Hampshire/ zero valent iron	Combination of surface precipitation and adsorption through surface complexation. The main adsorption reaction is that of As forming mono- and bi-dentate complexes with ferric hydroxides
University of Waterloo/ zero-valent iron co-precipitation	Oxidation, co-precipitation, adsorption, and filtration process
2004 Contest	
Dalhousie University/ coal fly ash adsorption	fly ash column with adjusted pH
Montana Tech/ silica PEI gel	filter with a mixture of sand and silica polyethyleneimine (PEI) gel for chelation
Ohio State University/ granular ferric hydroxide adsorbent	The columns operate in series with two columns on-line and one column off-line at all times. The second column in series provides a safety factor.
Widener University/ Extraction with collagen dispersions	Collagen dispersions, manufactured from bovine corium, have a wide range of applicability including bi-phasic separations
2005 Contest	
Clemson University/ Iron adsorption	System consists of an iron and sand column to remove arsenic followed by a pH adjustment and a series of two iron and sand columns to remove nitrate, followed by pH adjustment and hypochlorite addition to the system to remove by-products of the nitrate removal process
Duke University/ Filtration	Simple disposable filters containing activated carbon coated with ferric hydroxide
Lafayette College/ Adsorptive	Iron-enhanced activated alumina
Montana Tech/ silica polyethyleneimine (PEI) gel	Polyethyleneimine (PEI) on a silica gel backbone with a zirconium metal chelated to it
NM State University/ filtration	activated alumina filter

* award winners in bold font; full list at <http://www.werc.net/contest>

Author biographies

Dr. Malcolm Siegel is a Principal Member of the Technical Staff at Sandia National Laboratories. He received a BA in Chemistry from Columbia University; a Ph.D. in Geological Sciences/Geochemistry from Harvard University, and a Masters in Public Health/Epidemiology from the University of New Mexico. Dr. Siegel has served as Principal Investigator for experimental and modeling studies of radionuclide retardation and hydrogeochemical studies at the Waste Isolation Pilot Plant Site and Yucca Mountain, as the Technical Coordinator of the U.S. DOE Innovative Treatment and Remediation Demonstration program and as the Project Manager for the Sandia Arsenic Treatment Technology Pilot Demonstration Program. He is the author of over 55 scientific articles, book chapters and peer-reviewed reports.

Paul McConnell is a Principal Member of the Technical Staff at Sandia National Laboratories. He is in the Material Transportation Risk Assessment & Security Department, but is currently assigned to the Arsenic Water Technology Partnership and the Rural Arsenic Water Treatment Outreach projects. Mr. McConnell is a metallurgical engineer with degrees from Case Western Reserve University and the University of British Columbia. He has many years of experience related to the packaging of radioactive materials. Recently he has been involved in developing techniques for the mitigation of waterborne radioactive contaminants.

Albert Ilges has been with the Awwa Research Foundation for more than 13 years and has held positions as a Project Manager, Senior Project Manager, and is the Arsenic Program Manager for the Arsenic Water Technology Partnership. He has served as the Chair of the Arsenic Partnership Management Committee and actively managing several arsenic partnership research projects. Prior to joining AwwaRF Albert worked for a public drinking water utility for more than 5 years, first in operations and then as laboratory director. As Lab Director he oversaw the implementation of the Lead and Copper Rule requirements, sampling plan and the corrosion control experiments which resulted in a successful corrosion control program.

Dr. Hsiao-wen Chen is a Project Manager at Awwa Research Foundation. The projects she oversees include research on innovative arsenic removal technologies sponsored by the Arsenic Water Technology Program. She has a Ph.D. degree in environmental engineering from the University of Colorado at Boulder and has 11 years of experience in arsenic chemistry, occurrence, and treatment.

Dr. Abbas Ghassemi received a BS, Chemical Engineering, University of Oklahoma, 1979; and MS and Ph.D. in Chemical Engineering, New Mexico State University, in 1989 and 1990. He is currently a full professor in Chemical Engineering at NMSU and the Executive Director of WERC: A Consortium for Environmental Education and Technology Development, at NMSU. As the Executive Director of WERC, he is the Chief Operating Officer for programs of over \$5-million annually in education and research, managing activities between 4 academic institutions, 2 National Laboratories and several industrial organizations. He is responsible for administrative duties, operation, budget, planning, and personnel supervision for the program; formulation, coordination, and implementation of WERC's activities; and interaction and involvement of seventy (70) industrial and government agencies in all aspects of the WERC programs.

Roseann Thompson received a BA Geology and Geography 1985, Mount Holyoke College; a MS Geology in 1991, New Mexico State University; and a MPA Public Administration in 1998, New Mexico State University. She has 17 years of private, government and academic experience in the environmental and public administration fields. Rose is currently Project Manager at WERC. Her responsibilities include identifying and preparing proposals for external funding, preparing and up-dating research reports and documents, editing technical reports and documents, creating critical path management schedules for contamination/remediation projects, reports on grants, interacting with researchers and others on special projects, consulting with state and private agencies, planning and tracking of current technology projects and identification of critical financial and schedule issues for effective project management.